Eur J Appl Physiol (1989) 59:178-183

European Journal of Applied Physiology
and Occupational Physiology

Energy cost of running in similarly trained men and women

V. Bunc and J. Heller

Physical Culture Research Institute, Charles University, Újezd 450, CS-118 07 Prague 1, Czechoslovakia

Summary. The energy demand of running on a treadmill was studied in different groups of trained athletes of both sexes. We have not found any significant differences in the net energy cost (C) during running (expressed in $J \cdot kg^{-1} \cdot m^{-1}$) between similarly trained groups of men and women. For men and women respectively in adult middle distance runners $C = 3.57 \pm 0.15$ and 3.65 ± 0.20, in adult long-distance runners $C = 3.63 \pm 0.18$ and 3.70 ± 0.21, in adult canoeists $C = 3.82 \pm 0.34$ and 3.80 ± 0.24, in young middle-distance runners $C = 3.84 \pm 0.18$ and 3.78 ± 0.26 and in young long-distance runners $C = 3.85 \pm 0.12$ and 3.80 ± 0.24. This similarity may be explained by the similar training states of both sexes, resulting from the intense training which did not differ in its relative intensity and frequency between the groups of men and women. A negative relationship was found between the energy cost of running and maximal oxygen uptake ($\dot{V}_{O_{2max}}$) expressed relative to body weight (for men $r = -0.471, p < 0.001$; for women $r = -0.589$, $p < 0.001$). In contrast, no significant relationship was found in either sex between the energy cost of running and $\dot{V}_{O_{2max}}$. We conclude therefore that differences in sports performance between similarly trained men and women are related to differences in $\dot{V}_{O_{2max}} \cdot kg^{-1}$. The evaluation of C as an additional characteristic during laboratory tests may help us to ascertain, along with other parameters, not only the effectiveness of the training procedure, but also to evaluate the technique performed.

Key words: Energy cost of running — Maximal oxygen uptake — Sex differences

Introduction

The energy requirement of motor activity is one of the basic parameters by means of which we can characterize the influence of this activity on the body. The general relationship between intensity of exercise (i) and energy output ($\dot{E}$) may be expressed as follows (Åstrand and Rodahl 1977; Bunc et al. 1987b; Davies 1980; Pugh 1970, 1971):

$$\dot{E} = C' \cdot i^n \quad \text{where} \quad n = 1\text{-}3 \qquad (1)$$

The above relationship is true for all ranges of exercise intensities, in our case running speeds.

With a constant speed of running, at submaximal exercise intensities, the relationship between $\dot{E}$ and speed of running (v) is linear, i.e. the metabolic power output, necessary to proceed at a given running speed, can be regarded as the product of energy spent per unit distance C times the speed itself:

$$\dot{E} = C \cdot v \qquad (2)$$

where C, defined as the energy cost of running, is expressed in $J \cdot kg^{-1} \cdot m^{-1}$ and running speed in $m \cdot s^{-1}$, thus yielding energy $\dot{E}$ in $W \cdot kg^{-1}$. The range of linearity depends on training, metabolic state, age, sex and speed potential of the subjects studied (Åstrand and Rodahl 1977; Bunc et al. 1987b; di Prampero et al. 1986; Menier and Pugh 1968).

Direct measurement of $\dot{E}$ during real physical activity is very complicated. For practical reasons, we have often expressed $\dot{E}$ as oxygen uptake ($\dot{V}_{O_2}$) for the activity. In these cases it has been convenient to express C in $ml \cdot kg^{-1} \cdot m^{-1}$ and/or $J \cdot kg^{-1} \cdot m^{-1}$ and running speed in $m \cdot min^{-1}$, to

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Offprint requests to: V. Bunc

obtain $\dot{E}$ in more customary units, $ml \cdot kg^{-1} \cdot min^{-1}$. Thus Eq. 2 may be rearranged as follows:

$$\dot{V}_{O_2} = C \cdot v \tag{3}$$

By rearranging Eq. 2 and applying it to maximal conditions, it can be seen that maximal energy output ($\dot{E}_{max}$) is the product of maximal $v_{max}{}^n$ times C:

$$\dot{E}_{max} = C \cdot v_{max}{}^n \tag{4}$$

This equation is independent of the sources, aerobic and/or anaerobic, that provide the energy for muscular contraction. Under aerobic conditions, since $\dot{E}_{max}$ can be identified with $\dot{V}_{O_{2max}}$, in the submaximal range of v, equation (3) becomes:

$$f \cdot \dot{V}_{O_{2max}} = C \cdot v \tag{5}$$

where f is the fraction of $\dot{V}_{O_{2max}}$ which may be utilized over a prolonged period of time (Bunc et al. 1987b; di Prampero et al. 1986). The duration of competition and thus also the performance in training is obviously a decisive factor in determining the magnitude of f. It is larger the longer the duration of the competitive performance (Bunc et al. 1987a).

Although many studies have examined various aspects of C, relatively few have made a simultaneous assessment of C in trained men and women (Bransford and Howley 1977; Falls and Humphrey 1976). The aim of this study was to assess C in relatively similarly trained men and women from differing sports. Running was chosen as it is one activity to which the human body is highly adapted.

Materials and methods

Groups of young and adult athletes of both sexes, specializing in differing sports, exercised on a treadmill at a slope of 5% with stepwise increases in spead to subjective exhaustion. Selected anthropometric and some maximal functional parameters of the subjects studied are presented in Table 1. The initial speed on the treadmill was 10 $km \cdot h^{-1}$ in middle-distance runners (junior female); 12 $km \cdot h^{-1}$ in canoeists (adult women) and long-distance runners (junior female); 13 $km \cdot h^{-1}$ in long-distance runners (adult women) and middle-distance runners (junior male); 14 $km \cdot h^{-1}$ in middle-distance runners (adult women) canoeists (adult male) and long-distance runners (junior male); 15 $km \cdot h^{-1}$ in middle-distance runners (adult male) and long-distance runners (adult male). The speed of running was increased every min by 1 $km \cdot h^{-1}$. All measurements were made towards the end of the preparatory period of a seasonal training schedule for the particular sports events.

Respiratory parameters were measured using an open system. The athletes breathed into a two-way valve with a small dead space. Pulmonary ventilation ($\dot{V}_E$) expressed at body temperature, pressure and saturation was measured by a pneumotachometer (Jaeger, FRG) calibrated before and after every test by a mechanical pump. The $\dot{V}_{O_2}$ and carbon dioxide ($\dot{C}O_2$) output were measured in expired air and expressed at standard temperature and pressure, dry. Oxygen concentration was measured by a thermal analyser (zircon cell) and CO_2 concentration by an infrared analyser (both Jaeger, FRG) and were

Table 1. Selected physical characteristics of the subjects studied (mean ± SD)

	n	Age (year)	Mass (kg)	Height (cm)	$\dot{V}_{O_{2max}} \cdot kg^{-1}$ ($ml \cdot kg^{-1} \cdot min^{-1}$)	$\dot{V}_{O_{2max}}$ ($l \cdot min^{-1}$)
Middle-distance	8	23.8	66.4	180.3	70.93	4.71
runners (adult male)		±3.1	±4.0	±3.0	±4.12	±0.33
Middle-distance	8	23.2	52.3	167.2	62.00	3.24
runners (adult female)		±2.9	±4.9	±5.3	±3.92	±0.39
Long-distance	17	24.1	62.4	176.3	72.27	4.51
runners (adult male)		±3.3	±3.4	±2.7	±3.92	±0.34
Long-distance	6	24.2	51.6	164.4	65.87	3.40
runners (adult female)		±2.2	±4.1	±6.2	±4.11	±0.31
Canoeists (adult male)	28	22.8	79.2	180.2	62.29	4.93
		±3.3	±4.5	±5.6	±4.32	±0.64
Canoeists (adult female)	7	21.1	67.3	169.4	49.96	3.36
		±2.1	±6.2	±4.3	±2.94	±0.40
Middle-distance	16	16.5	62.1	178.4	67.12	4.17
runners (junior male)		±0.7	±4.3	±4.2	±5.04	±0.29
Middle-distance	12	16.1	51.0	163.4	54.51	2.78
runners (junior female)		±0.6	±5.3	±4.6	±2.64	±0.34
Long-distance	19	16,9	63.4	177.6	66.94	4.24
runners (junior male)		±0.8	±4.3	±4.1	±4.02	±0.39
Long-distance	7	17.1	52.2	165.2	57.29	2.99
runners (junior female)		±0.7	±4.3	±4.7	±2.48	±0.19

checked before and after very test by a calibrating gas mixture of a known concentration. Before each series of measurements, the linearity of both analysers was checked. Heart rate was determined by means of a digital cardiotachometer (Hellige, FRG). A computer printed the values every 30 s. Maximal values were calculated from two consecutive highest values.

Coefficients C were calculated from the maximal i where a reliable relationship between i and $\dot{E}$ still existed, i.e. at the point of the so-called anaerobic threshold, in our case at the level of the ventilatory threshold (VT) (Bunc et al. 1984, 1986; Komi et al. 1981). The v at VT was converted from the value determined at the 5% slope to 0% according to our previous results (Bunc et al. 1980) and these transformed values were used for the calculation of C.

The VT was assessed with the help of a computer algorithm by means of a two-compartment linear model from the relationship of $\dot{V}_E$ to $\dot{V}_{O_2}$ or $\dot{C}O_2$ as an intersection point between two regression lines (Bunc et al. 1984, 1987a). The v and $\dot{V}_{O_2}$ at VT level were determined by linear interpolation.

Means and standard deviations were calculated according to standard methods. Pearson correlation analyses were performed on the relevant data. Unpaired Student's t-tests were used to evaluate differences in the appropriate data.

Results

Values of $\dot{V}_{O_{2max}}$ and $\dot{V}_{O_{2max}}$ related to body mass are presented in Table 1. All the values of these variables are significantly higher in the groups of men than in the groups of women. The maximal mean difference in $\dot{V}_{O_{2max}}$ was found in junior middle-distance runners (33.3% of the values for males) and minimal in adult long-distance runners (24.6% of the values for males). In $\dot{V}_{O_{2max}}$ related to body mass maximal differences were found in canoeists (19.8% of the values for males), and minimal differences in adult long-distance runners (8.8% of the values for males).

The differences in $\dot{V}_{O_{2max}} \cdot kg^{-1}$ between male and female athletes from the same sport are practically the same (in terms of the percentage of the values for males) as those in sports performance (again in terms of the percentage of the performance of males).

Table 2. Values for the coefficient of the energy cost of running (C) in different groups of trained men and women (mean ± SD)

	C ($J \cdot kg^{-1} \cdot m^{-1}$)	
	Male	Female
Middle-distance runners	3.57	3.65
	0.15	0.20
Long-distance runners	3.63	3.70
	0.18	0.21
Canoeists	3.82	3.80
	0.34	0.24
Middle-distance runners (junior)	3.84	3.78
	0.19	0.26
Long-distance runners (junior)	3.85	3.80
	0.12	0.24

Mean values of C are presented in Table 2. The lowest values of this coefficient were found in adult male middle-distance runners (3.57 ± 0.15 $J \cdot kg^{-1} \cdot m^{-1}$). On the other hand, the highest values were found in young male long-distance runners (3.85 ± 0.12 $J \cdot kg^{-1} \cdot m^{-1}$). The intersex differences in C between the athletes from the same sports are statistically non-significant, and may be ignored for practical purposes. The differences between sexes (in percentages of mean values) ranged from 2.2% (adult middle-distance runners) to 0.5% (canoeists).

The values of C in adults were found to be significantly lower than in junior athletes of the same sporting events ($p < 0.01$ in all cases).

The coefficient of C demonstrated a highly

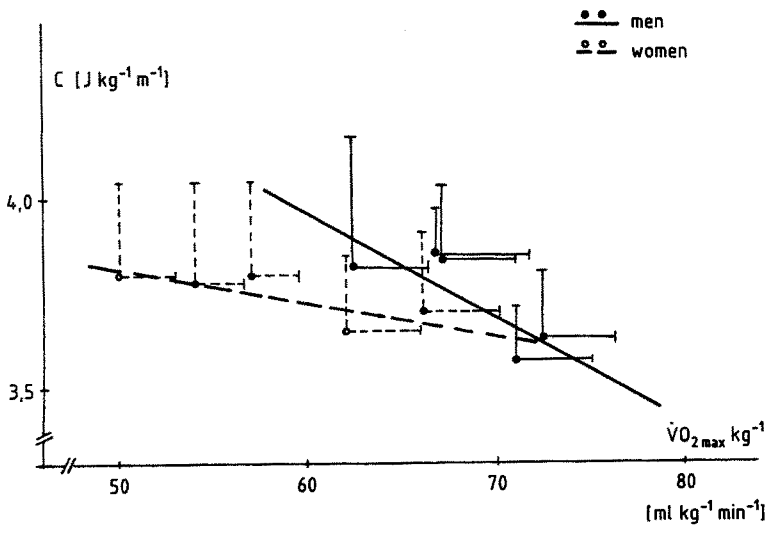

Fig. 1. Relationship between the energy cost of running on the treadmill (C) and maximal oxygen uptake related to body mass ($\dot{V}_{O_{2max}} \cdot kg^{-1}$) in different groups of trained *men* and *women* $y = -0.027x + 5.547$, $n = 88$, $r = -0.471$ (in *men*), $y = -0.009x + 4.245$, $n = 40$, $r = -0.589$ (in *women*)

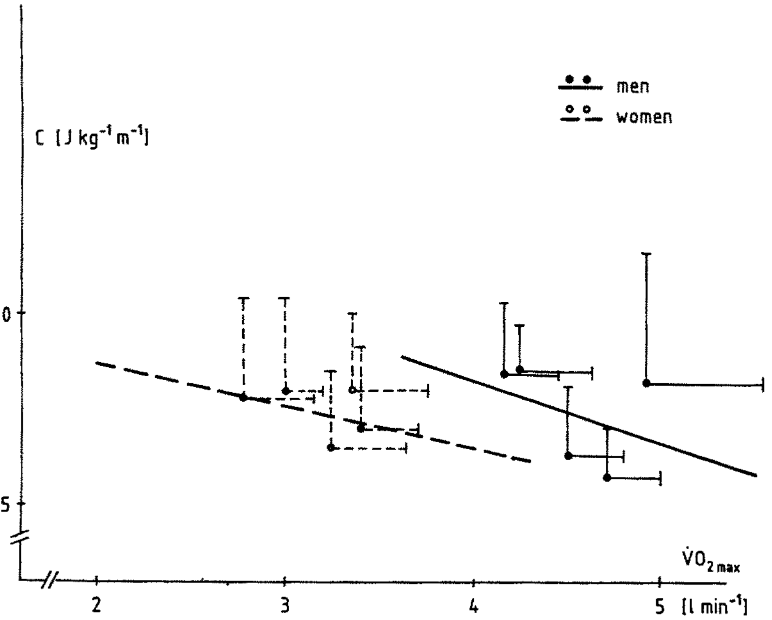

Fig. 2. Relationship between energy cost of running on the treadmill (*C*) and maximal oxygen uptake ($\dot{V}_{O_{2max}}$) in different groups of trained *men* and *women* $y = -0.158x + 4.457$, $n = 88$, $r = -0.207$ (in groups of *men*), $y = -0.108x + 4.088$, $n = 40$, $r = -0.320$ (in groups of *women*)

significant negative relationship with values of $\dot{V}_{O_{2\max}}$ related to body mass weight ($p < 0.001$ in all cases) (Fig. 1). In contrast, no significant relationship was found between coefficients *C* and absolute values of $\dot{V}_{O_{2\max}}$ (Fig. 2).

Discussion

The physiological differences responsible for the differences between the sexes in $\dot{V}_{O_{2\max}}$ have been a topic of interest for many years (Åstrand 1952; Drinkwater 1973; Sparling 1980; Cureton et al. 1986; von Dobeln 1956). Differences in the size of the organs of oxygen transport and musculature appear to be of primary importance since the percentage difference in $\dot{V}_{O_{2\max}}$ between men and women is reduced dramatically when $\dot{V}_{O_{2\max}}$ is expressed relative to body mass. Based on an analysis of 13 studies in the literature in which $\dot{V}_{O_{2\max}}$ of men and women was directly compared, Sparling (1980) reported average mean differences of 56% and 28% for $\dot{V}_{O_{2\max}}$ expressed in $\mathrm{l \cdot min^{-1}}$ and relative to body mass in $\mathrm{ml \cdot kg^{-1} \cdot min^{-1}}$ respectively. These differences were independent of the method of testing. However, the men and women in most studies were not matched as to their physical condition and/or state of training and Sparling concluded that differences in physical activity probably contributed to the magnitude of the sex differences observed.

In two studies of male and female runners and swimmers carefully matched as to their training history (Sparling and Cureton 1983; Zwiren et al. 1983) the differences in $\dot{V}_{O_{2\max}}$ expressed relative to body mass and fat-free mass were smaller, 18% and 3%-5%, respectively. These findings are in good agreement with our data. The small sex differences in $\dot{V}_{O_{2\max}}$ expressed relative to fat-free mass suggest that all but a very small proportion of $\dot{V}_{O_{2\max}}$ is related to dimensional differences between the sexes, if men and women are equally trained. The proportion of the sex difference in $\dot{V}_{O_{2\max}}$ not related to dimensional differences may be due to sex differences in haemoglobin concentration (Cureton et al. 1986).

The differences in $\dot{V}_{O_{2\max}} \cdot \mathrm{kg}^{-1}$ are very similar to those in sports performance. Assuming that the values of *C* and *f* are similar in equally trained men and women (Bunc et al. 1987a), we can conclude from Eq. 5 that the differences in *v*, i.e. in sports performance, between men and women are the result of differences in $\dot{V}_{O_{2\max}}$.

The overall average values of *C*, determined in our groups of athletes, are consistent with numerous previous observations (Bransford and Howley 1977; Conley and Krahenbuehl 1980; di Prampero et al. 1986; Falls and Humphrey 1976; Margaria 1938; Margaria et al. 1963; Menier and Pugh 1968). The highest values of the coefficient of variation in *C* amount to 6.8% (junior male long-distance runners) and suggest that variability in *C* may play a role in establishing performance, i.e. maximal *v* during a competition, as follows from Eq. 5. These coefficients of variability are lower by at least 35% than those of 9.5% presented by di Prampero et al. (1986). Our groups of athletes were much more homogeneous in performance and thus in their state of training than those observed by the above-mentioned authors.

Coefficient C can be used for the evaluation of the mode of transformation of metabolic (chemical) energy in the human body to mechanical work (mechanical adaptation). The higher the level of mechanical adaptation to a given type of exercise, the lower the amount of energy necessary to transfer 1 kg of body mass along a distance 1 m. It is for this reason that the lowest values of C were recorded in adult middle- and long-distance runners of both sexes. The lowest values of C in male adult middle-distance runners were obviously the result of a high level of adaptation to running of these athletes who were forced to exercise at very high speed. Another parameter having a significant influence on the high value of C is the technique of movement (Bunc et al. 1986) which was best in middle-distance runners (Costill 1979).

On the other hand, the mechanical adaptation to running and running technique in groups of junior middle- and long-distance runners and adult canoeists of both sexes is lower than in adult middle- and long-distance runners and, therefore, C in these athletes are higher than in those of adult middle- and long-distance runners.

The non-significant differences in C in trained men and women athletes are probably the result of the very similar intensities of their training and, thus, of the very similar adaptation to running in both sexes.

The non-significantly lower values of C in adult, male, middle- and long-distance runners than in female athletes in the same sports events, may probably be explained by a higher sports performance in men than in women.

Junior female middle- and long-distance runners and canoeists have non-significantly lower values of C as compared to males in the same sports events. This might be due firstly to a lower intensity of training and, therefore, to a lower competitive performance as compared to males from the same sport. Secondly, Bosco et al. (1980) showed that under equivalent training conditions there are, in women, better predispositions for a higher economy of exercise in the submaximal ranges, i.e. lower values of C, which result from a higher proportion of slow twitch fibres in their muscles than in males.

In his study published 7 years later, Bosco et al. (1987) showed a positive relationship between C and the percentage of fast twitch fibres. These results agree with the findings of Kaneko et al. (1983) who observed that the mechanical efficiency, correlated to C, of distance runners was appreciably higher (72%) than that observed in sprinters (47%) when running slowly ($3 \cdot 66\ \mathrm{m \cdot s^{-1}}$) and therefore C in long-distance runners must be smaller than in sprinters. These authors assume that distance runners have a higher percentage of slow twitch fibres, and explained their findings on the basis of the metabolic responses of slow twitch fibres. Evidence has been presented that slow twitch fibres show higher efficiency than fast twitch fibres when the contraction rate is low (Awan and Goldspink 1972; Wendt and Gibbs 1974).

The differences in C between adult and junior athletes can be explained by different racing performance and obviously also by a different number of years of training. These differences are significant in middle- and long-distance male runners ($p<0.01$ in both cases). In these groups of athletes, the differences in competitive performance are grater according to age. This finding agrees with those of Costill (1979) who showed that the endurance runner is at his best when aged between 27 and 32 years and that runners aged between 18 and 23 years do not perform as well, since many of them possess the physiological qualities generally associated with success in long-distance performance. The cause must obviously be in the subtle muscular adaptation achieved only by years of sports training (Costill 1979).

The coefficients of C are constant within the range of exercise intensities where there is a linear relationship between v and $\dot{E}$. According to our measurements, it is constant within the range 20%-90% $\dot{V}_{\mathrm{O}_{2\max}}$ (Bunc et al. 1986).

In these experiments, C was determined on a treadmill where air resistance is zero. In the above range of intensities there is a mean difference in $\dot{E}$ for running on the treadmill, and on flat ground, of approximately 6% or less (Bunc et al. 1987b; Davies 1980; Pugh 1970, 1971). The lesson we drew from these experiments is that, when using these coefficients in practical situations, for v higher than $13\ \mathrm{km \cdot h^{-1}}$, coefficient C must be increased by about 6%.

The negative relationship between $\dot{V}_{\mathrm{O}_{2\max}}$ expressed relative to body mass and C means that athletes with higher values of $\dot{V}_{\mathrm{O}_{2\max}} \cdot \mathrm{kg}^{-1}$ have lower values of C, i.e. greater running economy. These findings may be the result of the prolonged duration of the competitions and, thus, of the training performance of these athletes when they are forced to turn out a highly economical performance over a prolonged period of time, and it may also be the result of a high degree of adaptation to running.

Evaluation of the degree of adaptation, with the help of C as an additional characteristic during laboratory tests, enables us to ascertain, along with other parameters, not only the effectiveness of training procedures, but it also helps in evaluating the technique of the movement performed. This is essential in sports events where training is started at an early age and enables us to determine the energy cost of the training stimulus used.

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Accepted March 29, 1989